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On the alpha decay of strongly deformed odd-*A* nuclei

By OWE PRIOR

With 1 figure in the text

The probability of alpha decay is usually assumed to be expressible as the product of the probability of formation of the alpha particle and the probability of its penetration through the Coulomb barrier. The theory of barrier penetration originally put forth by Gamow and others (ref. 1, 2) has been generalized by Fröman (ref. 3) and by Rasmussen and Segall (refs. 4 and 5) to include the case of deformed nuclei. As to the formation process no complete description is available. However, as has been known for a long time experimentally (the empirical Geiger–Nuttal relation), the lifetimes of even-even alpha emitters of different energies are directly proportional to the inverse of the barrier penetration probability. That is to say, the formation probability of the alpha particle appears to be the same for all even-even alpha emitters. Most odd-*A* alpha decays proceed with transition rates that are slower by a factor $\sim 10\text{–}10^5$ than the alpha decays of even-even nuclei of the same transition energies. It is convenient then to define a hindrance factor F as

$$F = T^{(i)}_{\frac{1}{2}}/T^{(0)}_{\frac{1}{2}},$$

where $T^{(i)}_{\frac{1}{2}}$ is the partial half life of the alpha group i in an odd-A nucleus, and the quantity $T^{(0)}_{\frac{1}{2}}$ is the half life for a ground state transition of the same energy in an even-even nucleus.

There appear, however, a few outstanding alpha branches that have $F \sim 1$, the so-called favoured transitions. It was noted by Bohr, Fröman and Mottelson (ref. 6) and by J. O. Newton (ref. 7) that these all correspond to cases, where the odd-*A* nucleon in parent and daughter is left in the same intrinsic state. In deformed nuclei (to which group of nuclei most alpha emitters belong) the intrinsic states are basically characterized by the total angular momentum of the nucleons along the nuclear symmetry axis Ω. These states are doubly degenerate corresponding to an assumed reflection symmetry of the nucleus relative to a plane perpendicular to the axis of deformation. The two nucleons that may fill such a nucleonic level may be thought of as describing the same orbital but corresponding to opposite direction of motion. These particles, being strongly correlated, form a stable pair with vanishing total angular momentum. According to the picture suggested by Bohr, Fröman and Mottelson (ref. 6) and by

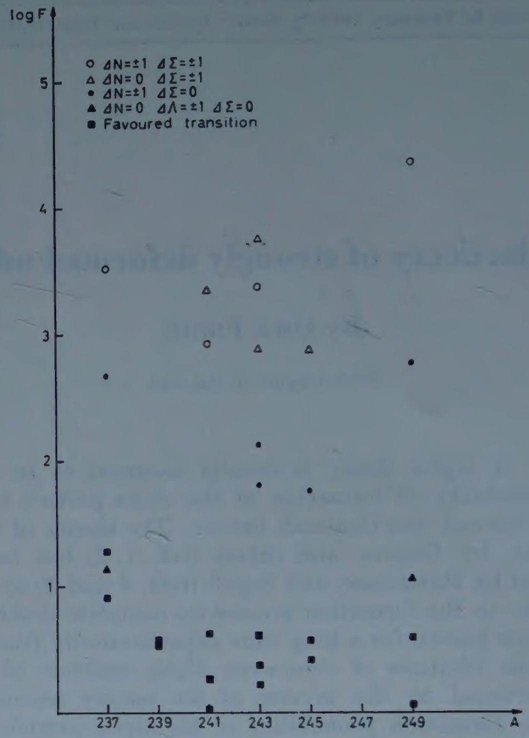

Fig. 1. Diagram exhibiting hindrance factors (logarithmic scale) for α-decay of odd-A nuclei in the mass region $237 \leqslant A \leqslant 249$. For identification of the particular transitions see table 1.

Newton (ref. 7), the alpha particle is now readily formed out of the two pairs of neutrons and of protons that occupy the last filled orbitals. In favoured transitions the situation is the same as for even-even nuclei, except that there is then the odd nucleon which remains in its orbital in this case. Therefore the favoured transition usually leads to an excited state in the daughter nuclide.

In the case of unfavoured odd-A transitions, however, the last odd particle occupies a different orbital for parent and daughter. The alpha particle then, in a way of speaking, is no longer formed from only Ω-paired nucleons but from more or less poorly overlapping states. As no complete theory for alpha formation is available at present (for a promising development in this field see, however, H. J. Mang, *Zeits. f. Physik*, *148*, 582 (1957)), it may be of interest to correlate the hindrance factor F with the changes in the so-called asymptotic quantum numbers characterizing the single particle orbitals of deformed nuclei (see B. Mottelson and S. G. Nilsson, ref. 8, for the classification of the experimental spectra in this region of nuclei). These approximate quantum numbers have the following significance. Σ and Λ are the components of spin and orbital angular momentum of the odd particle along the nuclear symmetry axis, while N and n_z, respectively, are the total number of nodes of the wave function and the number of nodal planes perpendicular to the symmetry axis.

Table 1. The hindrance factors of α-transitions of odd-A nuclei.

Columns 1 and 2 list the parent nuclide with its assigned quantum numbers $[N, n_z, \Lambda, K]$. In all cases he total angular momentum I equals K. Columns 3 and 4 identify in the same way the state in the daughter nuclide to which the transition proceeds. Columns 5–8 give the differences in the "asymptot-c" quantum numbers N, n_z, Λ, and Σ. Columns 9–11 supply the experimental information from which the hindrance factor may be calculated using the Fröman estimate (the relation VII-2 of ref. 6) for $T^{(0)}_{\frac{1}{2}}$. Column 12, finally, gives the logarithm of the hindrance factor F.

Parent nucleus	Orbital	Daughter nucleus	Orbital	ΔN	Δn_z	$\Delta\Lambda$	$\Delta\Sigma$	Intensity (%)	$T^{\alpha}_{\frac{1}{2}}$	E_α (MeV)	$^{10}\log F$
				Odd-Z nuclei							
$^{144}_{93}\mathrm{Np}^{237}$	[642 5/2]	$^{142}_{91}\mathrm{Pa}^{233}$	[530 1/2]	−1	−1	−2	0	2.8	$2.2 \times 10^6 y$	4.872	2.68
	[642 5/2]		[642 5/2]	0	0	0	0	42.0		4.787	0.92
	[642 5/2]		[651 3/2]	0	+1	−1	0	4.0		4.674	1.14
$^{144}_{95}\mathrm{Am}^{239}$	[523 5/2]	$^{142}_{93}\mathrm{Np}^{235}$	[523 5/2]	0	0	0	0	100	$30y$	5.75	0.54
$^{146}_{95}\mathrm{Am}^{241}$	[523 5/2]	$^{144}_{93}\mathrm{Np}^{237}$	[642 5/2]	+1	+2	−1	+1	0.4	$461y$	5.535	2.92
	[523 5/2]		[523 5/2]	0	0	0	0	84		5.476	0.26
	[523 5/2]		[521 3/2]	0	0	−2	+1	0.004		5.27	3.34
$^{148}_{95}\mathrm{Am}^{243}$	[523 5/2]	$^{146}_{93}\mathrm{Np}^{239}$	[642 5/2]	+1	+2	−1	+1	0.17	$7.9 \times 10^3 y$	5.339	3.38
	[523 5/2]		[523 5/2]	0	0	0	0	87		5.226	0.22
$^{146}_{97}\mathrm{Bk}^{243}$	[521 3/2]	$^{144}_{95}\mathrm{Am}^{239}$	[523 5/2]	0	0	+2	−1	30	$120d$	6.720	2.88
	[521 3/2]		[642 5/2]	+1	+2	+1	0	53		6.533	1.80
	[521 3/2]		[521 3/2]	0	0	0	0	17		6.184	0.62
$^{148}_{97}\mathrm{Bk}^{245}$	[521 3/2]	$^{146}_{95}\mathrm{Am}^{241}$	[523 5/2]	0	0	+2	−1	32	$14y$	6.37	2.88
	[521 3/2]		[642 5/2]	+1	+2	+1	0	41		6.16	1.75
	[521 3/2]		[521 3/2]	0	0	0	0	27		5.90	0.58
$^{152}_{97}\mathrm{Bk}^{249}$	[633 7/2]		[633 7/2]	0	0	0	0	6	$1 \times 10^5 y$	5.06	0.06
	[633 7/2]		[642 5/2]	0	+1	−1	0	94		5.40	1.05
				Odd-N nuclei							
$^{143}_{94}\mathrm{Pu}^{237}$	[743 7/2]	$^{141}_{92}\mathrm{U}^{233}$	[633 5/2]	−1	−1	0	−1	20	$\sim 4 \times 10^3 y$	5.69	~3.5
	[743 7/2]		[743 7/2]	0	0	0	0	80		5.40	1.29
$^{145}_{94}\mathrm{Pu}^{239}$	[631 1/2]	$^{143}_{92}\mathrm{U}^{235}$	[631 1/2]	0	0	0	0	72	$2.4 \times 10^4 y$	5.150	0.59
$^{147}_{94}\mathrm{Pu}^{241}$	[622 5/2]	$^{145}_{92}\mathrm{U}^{237}$	[622 5/2]	0	0	0	0	75	$\sim 3 \times 10^5 y$	4.893	~0
$^{145}_{96}\mathrm{Cm}^{241}$	[631 1/2]	$^{143}_{94}\mathrm{Pu}^{237}$	[631 1/2]	0	0	0	0	100	$10y$	5.950	0.63
$^{147}_{96}\mathrm{Cm}^{243}$	[622 5/2]	$^{145}_{94}\mathrm{Pu}^{239}$	[631 1/2]	0	+1	−1	−1	1	$35y$	6.061	3.74
	[622 5/2]		[622 5/2]	0	0	0	0	75		5.777	0.38
	[622 5/2]		[743 7/2]	+1	+2	+1	0	0.4		5.679	2.11
$^{149}_{96}\mathrm{Cm}^{245}$	[624 7/2]	$^{147}_{94}\mathrm{Pu}^{241}$	[624 7/2]	0	0	0	0	~77	$1 \times 10^4 y$	5.36	0.42
$^{151}_{98}\mathrm{Cf}^{249}$	[734 9/2]	$^{149}_{96}\mathrm{Cm}^{245}$	[624 7/2]	−1	−1	−1	−1	1.8	$5 \times 10^2 y$	6.19	4.33
	[734 9/2]		[622 5/2]	−1	−1	−2	0	3.3		5.94	2.77
	[734 9/2]		[734 9/2]	0	0	0	0	83.7		5.80	0.60

By using the experimental values of $T_{\frac{1}{2}}^{(i)}$ and of the alpha particle energy E_α of ref. 8 the quantity log F has been calculated for transitions in the mass-region $237 \leqslant A \leqslant 249$ (Table 1 and Fig. 1). Only transitions leading to the ground state of a rotational band are studied here. The relative branching to the different members of a band has been studied for some cases by Fröman (ref. 3).

It is now found that one may separate the transitions into different groups correlated with changes in these quantum numbers. First, with $F \sim 1$–4 one finds most of the favoured transitions. With $F \sim 8$–20 there are a few favoured transitions and a few transitions associated with final states that contain a large component (due to Coriolis mixing) of the state to which the favoured transition proceeds. The favoured transitions are then correspondingly weakened (see Mottelson and Nilsson, $A = 235$), as the transition strength is shared with the Coriolis coupled state.

For an F above 630 all transitions correspond to the spin being flipped ($\Delta\Sigma = \pm 1$). As the alpha particle is made up of nucleon pairs with zero relative spin one may expect a hindrance associated with $\Delta\Sigma \neq 0$, although the empirical hindrance factors appear much larger than what the purity of the quantum number Σ gives reason to expect.

Furthermore, F-values in the region $60 < F < 600$ all correspond to parent and daughter orbitals that have very poor overlap, which fact is mainly associated with a change in the quantum number N. For this latter group of transitions $\Delta\Sigma = 0$.

It may finally be pointed out that the only observed transition with $F > 10^4$ corresponds to both ΔN and $\Delta\Sigma$ being different from zero.

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Institute of Theoretical Physics, University of Lund, Lund, Sweden.

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